TITLE OF THE INVENTION

SUPERCONDUCTOR CONNECTION STRUCTURE

BACKGROUND OF THE INVENTION

5   Field of the Invention

The present invention relates to a superconducting line, superconducting line connection structure and production method thereof. To put it more specifically, the present invention applies to a superconducting

10   magnet system, current lead, power transmission cable, nuclear magnetic resonance analyzer, magnetic resonance diagnostic apparatus for medical use, superconducting power storage apparatus, magnetic separation apparatus, single crystal pulling apparatus in magnetic field, refrigerator cooling

15   superconducting magnet apparatus, superconducting energy storage, superconducting generator and magnet for nuclear fusion reactor.

Description of Prior Art

20   A superconducting magnet apparatus, superconducting power cable or the like may requires electrical connection of two or more superconducting lines. For example, electric resistance at a connection point must be minimized in the permanent

25   current operated superconducting magnet apparatus, thereby reducing the damping factor of magnetic field

produced by a magnet. Further, refrigerant consumption
is increased by heat generated at the connection point
in a superconducting power cable carrying a large
current. This requires electric resistance to be

5   reduced at the connection. A method for electrical
connection of two or more superconducting lines is
found in Japanese Application Patent Laid-Open
Publication No. 2001-102105 which discloses a method
for solidifying the superconducting line subsequent to

10 soaking of it in the melt of metal or alloy.

SUMMARY OF THE INVENTION

As shown in the description of the prior art, a
superconducting line can be electrically connected by

15 a method for solidifying the superconducting line
subsequent to soaking of it in the melt of metal or
alloy. This method, however, involves complicated
steps and a complex structure. Further, critical
magnetic field of the metal or alloy is 1T or less,

20 and the connection point cannot be laid out in high
magnetic field. Moreover, there remains a problem of
the superconducting line being denatured due to metal
melt at about 500 degrees Celsius, resulting in
deteriorated superconducting characteristics.

25 An object of the present invention is to provide a
superconducting line connection structure capable of

solving these problems.

As reported in Nature 410, 63-64 (2001) published recently, magnesium diboride (MgB_2) has been found out to be superconducting.

5   (1) Critical temperature

MgB_2 has a critical temperature of 39K. This is the maximum value in prior art metal-based superconducting materials. When this material is used to constitute a superconducting line connection point, stability

10   margin is increased due to high critical temperature. This allows connection of a superconducting line where a quick transfer to normal conduction is provided, namely, quenching phenomenon is hard to occur. Further, liquid hydrogen and gas helium can be used as a

15   refrigerant because of high critical temperature.

    (2) Critical magnetic field

The critical magnetic field at 0T is about 18T. It does not exceed 10T when liquid helium is at 4.2K. According to the prior art connection technique in the

20   superconducting magnet, the critical magnetic field of the connection point may be reduced, and this was accompanies by the following restrictions: A connection point had to be installed at a small space away from the superconducting magnet or a magnetic

25   shield had to be provided outside the connection point. However, when the connection point of a

superconducting line is configured through the use of the material according to the present invention, the aforementioned restrictions are removed, with the result that a higher degree of freedom is assigned to
5 the configuration of a connection point.

(3) Bonding property

A tentative production of a powder-in-tube wire using MgB_2 without heat treatment is reported in recent years. This is realized by excellent bonding property
10 among MgB_2 particles. This feature is not found in other superconducting materials.

Further, production method of using no heat treatment for a wire is different from that of oxide superconducting line and other superconducting lines.
15 In view of the excellent feature of MgB_2 as a superconducting material as described above, the present inventors have been studying how to apply MgB_2 to the connection point of a superconducting line. To solve the aforementioned problems, the present
20 inventors have used the following means:

The superconducting line connection structure according to Claim 1 is based on the electrical connection structure between two or more superconducting lines characterized in that
25 superconducting powder including magnesium diboride is provided between the aforementioned superconducting

lines. Use of this structure provides a simple
structure where the aforementioned superconducting
powder alone is placed between the aforementioned
superconducting lines, with the result that the
5   superconducting line connection structure is
simplified.

The superconducting line connection structure
according to Claim 2 is based on the superconducting
line connection structure described in Claim 1, the
10   mixture of superconducting powder and metal powder is
added between the aforementioned superconducting lines
as an alternative to the aforementioned
superconducting powder, wherein metallic powder or
alloy powder having a melting point lower than the
15   superconducting powder is added to the mixture of
superconducting powder and metal powder. Use of this
structure allows a plastic metal to improve the
bonding property between particles of the
aforementioned superconducting powder, thereby
20   ensuring conduction of a large current.

The superconducting line connection structure
according to Claim 3 is based on the superconducting
line connection structure described in Claim 1 or 2
and characterized in that the average particle size of
25   the aforementioned superconducting powder is 20
microns or less. Use of this structure improves the

bonding property between particles of the
aforementioned superconducting powder, thereby
ensuring conduction of a large current.

The superconducting line connection structure
5   according to Claim 4 is based on the superconducting
line connection structure described in Claim 1 or 2,
and characterized in that the aforementioned
superconducting line and the aforementioned mixture of
superconducting powder and metal powder are enclosed
10   in a coating material made of a pure metal of gold,
silver, copper, platinum, palladium, aluminum, niobium,
lead, tin, magnesium, indium, tungsten, cobalt, nickel,
iron, tantalum or chromium, or an alloy containing at
least one of the aforementioned metals. Use of this
15   structure ensures that the aforementioned
superconducting powder or the aforementioned mixture
of superconducting powder and metal powder is not
dissipated or lost, whereby mechanically stable
connections are provided.

20   The superconducting line connection structure
according to Claim 5 is based on the superconducting
line connection structure described in Claim 1 or 2,
and characterized in that a superconducting filament
enclosed in the aforementioned superconducting line is
25   directly in contact with the aforementioned
superconducting powder at least on some portion of the

contact surface between the aforementioned
superconducting line and the aforementioned
superconducting powder. Use of this structure provides
a connection structure where no electric resistance
5   occurs between the aforementioned superconducting
lines.

    The superconducting line connection structure
according to Claim 6 is based on the superconducting
line connection structure described in Claim 1 or 2,
10   and characterized in that the density of the
aforementioned superconducting powder is 50 % or more
of theoretical density. Use of this structure improves
the bonding property between particles of the
aforementioned superconducting powder, thereby
15   ensuring conduction of a large current.

    The method for producing a superconducting line
connection structure according to Claim 7 is based on
the method for producing a superconducting line
connection structure described in Claim 1 or 2, and
20   characterized in that heat treatment of the
aforementioned superconducting line connection
structure has never been provided. Use of this method
ensures a connection structure without performances of
the aforementioned superconducting line being
25   deteriorated by heat treatment.

    The method for producing a superconducting line

connection structure according to Claim 8 is based on
the method for producing a superconducting line
connection structure described in Claim 1 or 2, and
characterized in that heating is performed to reach
5   the temperature equal to or higher than the range
where a part of any one of the aforementioned
superconducting line, the aforementioned
superconducting powder and the aforementioned pure
metal powder or the aforementioned alloy powder
10   included in the aforementioned mixture of
superconducting powder and metal powder melts down.
Use of this method improves the bonding property
between the aforementioned superconducting line, the
aforementioned superconducting powder particles and
15   the aforementioned mixture of superconducting powder,
thereby ensuring conduction of a large current.

The method for producing a superconducting line
connection structure according to Claim 9 is based on
the method for producing a superconducting line
20   connection structure described in Claim 4, and
comprises; (1) a first step of enclosing the
aforementioned superconducting line and the
aforementioned superconducting powder in a coating
material made of a pure metal of gold, silver, copper,
25   platinum, palladium, aluminum, niobium, lead, tin,
magnesium, indium, tungsten, cobalt, nickel, iron,

tantalum or chromium, or an alloy containing at least one of the aforementioned metals, and (2) a second step of deforming the portion produced in the first step by applying a pressure of 1 ton/cm² or more

5   thereto. Use of this method improves the bonding property the aforementioned superconducting line, the aforementioned superconducting powder particles and the particles of aforementioned mixture of superconducting powder and metal powder, thereby

10   ensuring conduction of a large current.

     The superconducting line connection structure according to Claim 10 is based on the superconducting line connection structure according to Claim 1 or 2, and characterized in that at least one of the

15   aforementioned multiple superconducting lines to be connected or the aforementioned multiple superconducting stranded wires has the critical temperature equal to or higher than that of magnesium diboride. Use of this structure, for example, allows

20   connection between oxide superconducting lines, between MgB₂-based superconducting lines, between oxide superconducting line and metal-based superconducting line, between oxide superconducting line and MgB₂-based superconducting line, and between MgB₂-based

25   superconducting line and metal-based superconducting line.

The superconducting line connection structure according to Claim 11 is based on the superconducting line connection structure described in Claim 1 or 2, and characterized in that the superconducting line to be connected is a superconducting stranded wire formed by twisting multiple superconducting lines. This superconducting line connection structure allows power consumption to be reduced due to low electric resistance even if the connection point is located in the magnetic field. The apparatus using this connection structure does not require the connection point to be located within range of low magnetic field. So the entire magnet can be designed in a compact configuration, and the structure of connection points can be simplified.

The superconducting line connection structure according to Claim 12 is based on the superconducting line connection structure according to Claim 11, and characterized in that the aforementioned superconducting stranded wire is a superconducting stranded wire inside a cable-in-conduit type forcibly cooled superconductor. This superconducting line connection structure allows power consumption to be reduced due to low electric resistance even if the connection point is located in the magnetic field. The apparatus using this connection structure does not

require the connection point to be located within range of low magnetic field. So the entire magnet can be designed in a compact configuration, and the structure of connection points can be simplified.

5   The superconducting magnet apparatus according to Claim 13 is characterized by comprising a superconducting line connection structure according to Claim 1 or 2.

       The superconducting magnet apparatus according to
10   Claim 14 is characterized by comprising a superconducting line connection method manufactured in the method for producing a superconducting line connection structure according to Claim 7. This superconducting magnet apparatus allows a large
15   current to be sent to a connection point, and permits power consumption to be reduced due to low electric resistance even if the connection point is located in the magnetic field. The apparatus using this connection structure does not require the connection
20   point to be located within range of low magnetic field. So the entire magnet can be designed in a compact configuration, and the structure of connection points can be simplified.

25   BRIEF DESCRIPTION OF THE DRAWINGS

       Fig. 1a is a front view of a superconducting line

with a connection part thereof representing embodiment 1;

Fig. 1b is a plane view of Fig. 1a;

Fig. 1c is a side view of Fig. 1a;

5   Fig. 2 is a cross sectional view of Fig. 1b taken along a line 101 in Fig. 1b;

Fig. 3 is a diagram representing the current/voltage characteristics of embodiment 1;

Fig. 4a is a front view of a superconducting line

10   with a connection part thereof representing embodiment 7;

Fig. 4b is a plane view of Fig. 4a;

Fig. 4c is a side view of Fig. 4a;

15   Fig. 5a is a vertical cross section of the superconducting line with the connecting portion thereof representing embodiment 7;

Fig. 5b is a horizontl sectional view of Fig. 5a;

Fig. 5c is a side view of Fig. 5a;

20   Fig. 6 is a conceptual view representing embodiment 8;

Fig. 7 is a cross section representing embodiment 9; and

Fig. 8 is a conceptual view representing a

25   forcibly cooled superconductor coil in embodiment 9.

DESCRIPTION OF REFERENCE NUMERALS

1a, 1b ... superconducting line to be connected,
2 ... MgB_2 powder, 3 ... coating material of connection
point, 4 ... superconducting filament, 1a, 11b ...
superconducting stranded wire, 12a, 12b ...

5   superconducting filament, 13a, 13b ... conduit, 14 ...
sleeve, 15 ... refrigerant discharge port, 21 ...
first layer superconducting coil, 22 ... second layer
superconducting coil, 23 ... third layer
superconducting coil, 24a, 24b ... gas cooled current

10   lead, 25a, 25b, 54a, 54b ... Bus bar, 26a, 26b ... bus
bar/superconducting line connection point, 27a, 27b ...
superconducting line/superconducting line connection
point, 28a ... lead inside the first layer coil,
28b ... lead outside the first layer coil, 28c ...

15   lead inside the second layer coil, 28d ... lead
outside the second layer coil, 28e ... lead inside the
third layer coil, 28f ... lead outside the third layer
coil, 29 ... cryostat, 30 ... liquid helium, 51a,
51b ... forcibly cooled superconducting coil, 52...

20   connection point, 53a, 53b ... bus bar connection
point, 55 ... power supply for coil excitation, 56 ...
super-critical pressure helium generating apparatus,
57 ... super-critical pressure helium discharge port
in super-critical pressure helium generating apparatus,

25   58 ... super-critical pressure helium suction port in
super-critical pressure helium generating apparatus,

101 ... cutting plane along cross sectional view.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiment 1

5   Figs. 1a to 1c are external views in the first
embodiment of a superconducting line connection
(hereinafter referred to as "connection point")
according to the present invention. Fig. 2 is a cross
sectional view representing the interior of the first
10   embodiment according to the present invention. Fig. 2
is a cross sectional view of the connection point
taken along a line 101 in Fig. 1b.

       The following describes the structure of the
connection point.

15   Reference numerals 1a and 1b denote
superconducting lines to be connected.

       The superconducting lines 1a and 1b are multi-
filament superconducting lines where niobium titanium
(NbTi) is used as a superconducting material and
20   anoxic copper is employed as a stabilizer. An NbTi
superconducting line was used in the present
embodiment, but other superconducting lines may be
used. The stabilizer was removed from superconducting
lines 1a and 1b, and superconducting filaments 4a and
25   4b are exposed inside the connection point. In the
present embodiment, the stabilizer was completely

eliminated, but part of the stabilizer may be left unremoved if the superconducting filament is brittle.

The coating material 3 of the connection point is arranged in a hollow structure of anoxic copper. The space between superconducting filaments 4a and 4b and the coating material 3 of the connection point is filled with MgB$_2$ powder 2.

The following describes how to produce the connection point: From the tip of two superconducting lines to be connected, the stabilizer of anoxic copper is removed by chemical treatment. In the present embodiment, nitric acid is used to remove the stabilizer, but it can be scraped off by mechanical means. The length of the stabilizer removed was about 30mm in the present embodiment. Two superconducting lines are the same, with a diameter of 0.7mm and a critical current of 800A in the external magnetic field of 0T. The superconducting line with stabilizer removed is inserted into a 60mm long pipe made of anoxic copper having an inner diameter of 5mm and an outer diameter of 10mm. The anoxic copper pipe is used as a coating material of the connection point in the final stage. The dimensions of the superconducting line, anoxic copper pipe and the like are determined to conform to the dimensions and characteristics of the superconducting line to be connected as well as

the environment where the connection point is arranged. If they are changed, the dimensions must also be changed. When the superconducting lines are inserted into the anoxic copper pipe, the superconducting

5   filaments is almost parallel and is preferably placed as close as possible to each other. After the end of the pipe on the side where two superconducting lines are inserted is crimped by a press, the anoxic copper pipe is filled with MgB_2 powder through the other end.

10   In this case, an appropriate amount of powder should be filled by giving consideration to the density and volume in the final stage, MgB_2 powder used in the present embodiment has an average particle size of 20 microns or less. After MgB_2 powder has been filled, the

15   uncrimped end of the pipe is also crimped by the pressed similarly to the case of the other end. Then the still uncrimped portion of the pipe, namely, the central portion of the pipe is crimped is crimped by the press so that the pipe has a rectangular section.

20   A press was used in the present embodiment, but any apparatus will do so long as the connection point can be mechanically compressed. Further, other configuration instead of a rectangular section can be used. The section of the connection point crimped by

25   the press is about 10mm wide and about 6mm thick. The position of MgB_2 powder in the section of the

connection point is about 8mm wide and 2mm thick.
Needless to say, these dimensions depend on the
dimensions of the superconducting line and pipe as
well as the amount of MgB_2 powder.

5   Fig. 3 shows the current/voltage characteristics
in liquid helium regarding the external magnetic field
of the superconducting line connection produced in the
aforementioned manner. Current flows between two
superconducting lines, and voltage is the value
10   between two points 10mm away from the coating material
of the connection point in each superconducting line.
As shown in Fig. 3, generation of voltage was not
observed up to 450A, and a superconducting state was
confirmed below 450A. Further, other superconducting
15   lines were also used to confirm the presence of
superconducting state. Critical current measuring
conditions mentioned above will be used in the
following description unless otherwise specified.

        As described above, it has been made clear that
20   MgB_2 powder enables electric connection of two
superconducting lines in the superconducting state.

        To improve current conduction, the present
inventors studied (1) dependency on MgB_2 powder
particle size of critical current at the connection
25   point, (2) the coating material of connection point,
(3) metal to be added to MgB_2 powder and the amount

thereof, (4) presence or absence of heat treatment and (5) density of MgB_2 powder. They manufactured a connection point and evaluated it.

The following describes the embodiments from 2 to 7:

Embodiment 2

MgB_2 powder with varying average particle sizes was prepared in advance, and a connection point was manufactured in the same method as Embodiment 1. The average particle size was measured by a scanning electron microscope, and the particle size of 95 % or more powder was confirmed to be within 20 % of the average particle size. MgB_2 powder is compressed to the density equivalent to 80 % ± 5 % of the theoretical density. Table 1 shows the relationship between the result of measuring the critical current of the connection produced in this way and the average particle size. Unless otherwise specified, it is assumed that anoxic copper is used for the coating material of the connection point, and the NbTi line described in Embodiment 1 is used for the superconducting line.

Table 1

Average particle size (µm)	8	11	14	17	20	23	26	29	32	35
Critical current (A)	490	440	480	460	450	350	340	310	280	210

As shown in Table 1, when the average particle size is 20 microns or more, the critical current tends to increase as the particle size increases. If it is below 20 microns, however, there is considered to be

5   no big change although there is a slight increase in the critical current. If it is 20 microns or more, the critical current is found to decrease. This is because, if the particle size is increased, close adhesion between particles is deteriorated and the

10 superconducting state cannot be maintained on the powder particle boundary. Another possible reason is that close adhesion between the filament of the superconducting line and MgB_2 powder is deteriorated. On the other hand, when the particle size does not

15 exceed 20 microns, there is only a slight increase of critical current. This is because there is an increase in the particle boundary on the portion where current flows although there is an excellent close adhesion between powder particles and between powder particles

20 and superconducting filaments. This is considered to have caused the rate of critical current increase to be reduced. As described above, it has been confirmed that critical current can be increased when the average particle size of MgB_2 powder is 20 microns or

25 less.

Embodiment 3

Using the pipe made of gold, silver, copper, platinum, palladium, aluminum, niobium, lead, tin, magnesium, indium, tungsten, cobalt, nickel, iron,

5   tantalum or chromium, the present inventors produced connection points according to the method as in Embodiment 1. It has been revealed that connection in the superconducting state is possible for all types. Especially copper, gold, silver and aluminum have

10   excellent spreading property; therefore, when the pipe was crimped, excellent correction structure was obtained without any crack on the surface. Connection points were produced using the pipes made of SUS304 stainless steel, copper/nickel alloy, silver/magnesium

15   alloy and the like, and it has been revealed that connection in the superconducting state is possible.

Embodiment 4

A given amount of indium powder having an average particle size 5 microns was added to MgB_2 powder having

20   an average particle size of 20 microns to produce connection points according to the method as in Embodiment 1. The result of measuring the critical current is shown in Table 2. Crimping was conducted at a surface pressure of 2 ton/cm^2 in the final crimping

25   operation. The percentage of addition in Table 2 denotes percentage by mass.

Table 2

Percentage of added indium powder (%)	0	0.01	0.1	1	10	25	40	50	60	70	75
Critical current (A)	450	420	440	490	510	600	420	300	120	10	0

As shown in Table 2, critical current has been confirmed to increase as the percentage of added indium powder is increased from zero. If the percentage reaches 25 % or more, critical current is found to decrease. When the percentage of addition does not exceed about 50 %, a connection point can be used sufficiently. When 25 % of indium powder was added, the cross section of the connection point was observed by a scanning electron microscope. Indium was not present over the entire boundary although indium is present on some portion of the boundary of MgB_2 powder particle. A greater portion was occupied by the bonded surface of MgB_2 powder particles. On the other hand, in case of the cross section of the connection point where 75 % was added, almost entire surface of $Mg B_2$ powder particles was covered by indium. In each case, there was no big change in the average size and configuration of MgB_2 powder particles. It can be estimated from these observations that soft indium powder was crushed among hard MgB_2 powder particles when crimped by a press and was arranged in the

clearances among MgB_2 powder particles. Therefore, bondage among MgB_2 powder particles was mechanically stable and MgB_2 powder particles were bonded with one another, with the result that critical current was

5   increased. However, as the percentage of addition was further increased, there was an increase increased in the mount of indium among MgB_2 powder particles. As the percentage was raised up to 75 %, the space among MgB_2 powder particles was completely filled with indium,

10   and there was no contact surface among MgB_2 powder particles. Thus, electric resistance of indium occurred all over, and the superconducting state did not occur as a whole. The present inventors used metal powder of lead and lead/tin alloy as an additive other

15   than indium, and made similar studies. It has been revealed that critical current was higher when added than when not added. Likewise, when the percentage of addition was increased over some level, critical current was reduced. Thus, it has been revealed that

20   addition of metal powder improves critical current.

Embodiment 5

As in the case with Embodiment 4, connection points were produced by adding indium powder to MgB_2 powder. In this case, however, the final crimping step

25   in Embodiment 1 was carried out by heating up to more than 157 degrees Celsius which is the melding point of

indium. Table 3 shows the dependency of the critical current on the percentage of added indium powder in this case. Added indium powder had an average particle size of 5 microns, the same size as above. The surface
5 pressure in the final crimping step by a press was 2 ton/cm^2, the same pressure as above.

Tale 3

Percentage of added indium powder (%)	0	0.01	0.1	1	10	25	40	50	60	70	75
Critical current (A)	450	480	550	670	690	650	430	310	100	20	0

Comparison between Tables 3 and 2 reveals that there is an increase in critical current on the whole. Further, it has been revealed that a bigger increase
15 in critical current results from smaller percentage of addition. The cross section of the connection point was observed by a scanning electron microscope. It has been shown that a higher density of MgB$_2$ powder particles a greater thickness of indium on the surface
20 of MgB$_2$ powder particles result from a smaller percentage of added powder. On the other hand, when the percentage of addition is 25 % or more, the thickness of indium among MgB$_2$ powder particles was increased, and bondage among MgB$_2$ powder particles was
25 poor, according to the observation by the present inventors. Thus, it has been revealed that, when

indium among MgB_2 powder particles were molten by
heating beyond the melting point of indium, critical
current can be increased by reducing the amount of
indium to be added, as compared to the case where it
5   is not heated. Further, the present inventors used
metal powder of lead and lead/tin alloy as an additive
other than indium, and made similar studies. It has
been revealed that critical current was higher when
added than when not added. These considerations have
10   lead them to conclude that, when a given metal or
alloy is added, heating beyond the melting point is
effective in improving critical current.

Embodiment 6

The present inventors produced connection points
15   where the density of MgB_2 was changed by changing
surface pressure in the final crimping stage, and each
critical current was measured. The production method
is the same as that described in Embodiment 1. Several
connection points were manufactured, wherein the
20   volumes of the MgB_2 portions in connection points were
kept unchanged. The average particle size of the MgB_2
powder is 20 microns. Table 4 shows the result of
measuring the critical current. Density in the Table
indicates the ratio between the density of MgB_2 in
25   actually manufactured connection points and the
theoretical density.

Table 4

Density ratio (%)	30	40	50	60	70	80	90
Critical current (A)	5	10	450	470	560	660	700

As shown in Table 4, an abrupt reduction of

5   critical current is observed when MgB$_2$ is 50 % or less.

This is considered to be caused by an increase in the

spacing among MgB$_2$ powder particles, with the result

that bondage can be hardly carried out in the

superconducting state. The result of measurement has

10   led to the conclusion that the density of MgB$_2$ must be

50 % or more of the theoretical density.

Embodiment 7

Figs. 4a to 4c each are an external view

representing the seventh embodiment of a

15   superconducting line connection point (hereinafter

referred to as "connection point") according to he

present invention. Figs. 5a and 5b are internal views

of the seventh embodiment according to the present

invention. Fig. 5a is a cross sectional view

20   representing a connection point, taken along a line

101 in Fig. 4b, Fig. 5b is a horizontal cross

sectional view of Fig. 5a, and Fig. 5c is a side view

of Fig. 5a.

The following describes the structure of the

25   connection point:

Reference numerals 1a and 1b denote

superconducting line to be connected. Any
superconducting line can be used, but in the present
embodiment, superconducting lines 1a and 1b are multi-
filament superconducting lines wherein the Bi-2212 is
5   used as a superconducting material and silver is
employed as a sheath material. The tip of each of two
superconducting lines is cut at an oblique angle, and
the angle between the cross section and the centerline
of the superconducting line is 30 deg. or less in the
10   present embodiment. The angle of the cross section
must be determined with consideration given to the
strength of the superconducting line and the like. In
principle, the angle can be within the entire range
from 90 to 180 degrees exclusive. In the cross section,
15   the superconducting filament of the superconducting
line is exposed to the outside. Two superconducting
lines are arranged in such a way that the cross
sections face each other. In the present embodiment,
the cross sections of superconducting lines face each
20   other, but other arrangements can also be used if the
filament and MgB_2 powder are in contact with each other.
Further, if electric resistance is assumed to occur to
the connection point, the arrangement which allows
current to pass through such a structure as sheath
25   material or separately inserted metal may be used,
wherein the filament and MgB_2 powder are not in direct

contact. The coating material 3 of the connection
point is a hollow structure made of anoxic copper, and
the space between the superconducting filaments 4a and
4b and coating material 3 of the connection point is

5   filled with MgB_2 powder 2.

The following describes how to manufacture the
connection point: The tips of the two superconducting
lines to be connected are each cut at an oblique angle,
and the angle between the cross section and the

10   centerline of the superconducting line should
preferably be an acute angle of 30 deg. or less. In
the present embodiment, this angle is about 20 deg. It
should be noted that the superconducting line to be
connected may have any cross section. In the present

15   embodiment, the cross section is a circle having a
diameter of 1.0mm. The superconducting line used is
the oxide superconducting line with a critical current
of 700A in the external magnetic field of 0T. The
superconducting line is inserted into the anoxic

20   copper pipe having a length of 60mm, inner diameter of
5mm and outer diameter of 10mm. This anoxic copper
pipe serves as a coating material of the connection
point. Then a press is used to crimp the end of the
pipe where the superconducting line is inserted. After

25   that, the pipe is filled with MgB_2 powder through the
other end. MgB_2 powder used in the present embodiment

has an average particle size of 20 microns. After the
other superconducting line has been inserted, the
still uncrimped end of the pipe is crimped. Then a
press is used to crimp the still uncrimped portion to
5   form the cross section of the pipe in a rectangular
shape. In this case, the cross section of the
connection point is bout 10 mm wide and about 6 mm
thick. Further, the portion of MgB_2 powder in the cross
section of the connection point is about 8 mm wide and
10   about 2 mm thick. As described above, the tips of the
two superconducting lines to be connected are each cut
at an oblique angle, and the angle between the cross
section and the centerline of the superconducting line
is an acute angle of 30 deg. or less. In the cross
15   section, the superconducting filament of the
superconducting line is exposed to the outside. MgB_2
powder is located between cross sections of the
superconducting lines and around the superconducting
lines. The coating material of the metal-made
20   connection point is placed further outside thereof.
This structure provides the following advantages:

(1) The angle between the cross section and
superconducting line centerline is an acute angle of
30 degrees. Compared to the case of 90 degrees, there
25   is an increase in the area of contact between the
superconducting filament and MgB_2 powder, and critical

current can be improved.

(2) Especially in the oxide superconducting line the superconducting filament is made of brittle ceramic, so it is difficult to expose the
5   superconducting filament as a single body to the outside by removing the stabilizer. However, a greater area of the superconducting filament can be exposed to the outside without removing the stabilizer by forming the tip of the superconducting line in an oblique
10   shape. This makes it possible to improve the critical current.

(3) By forming the tip of the superconducting line in an oblique shape, close adhesion between the superconducting filament and MgB_2 powder is improved
15   when crimping the coating material of the connection point in the direction at a right angle to the superconducting line. This allows critical current to be increased.

Table 5 shows the result of measuring the critical
20   current by changing the external magnetic field in the connection point produced according to the above-mentioned procedure.

Table 5

External magnetic field	0	0.1	0.2	0.5	1	2	5
Critical current (A)	700	550	400	350	330	310	290

As shown in Table 5, critical current is reduced
as the external magnetic field increases. However, it
has been revealed that this critical current has about
the same value as the original critical current of the
5   superconducting line to be connected. It has been
revealed, in other words, that critical current at the
portion of MgB$_2$ powder is greater that the critical
current of the superconducting line, and the
connection structure is excellent.

10   Embodiment 8

The following describes the superconducting magnet
system wherein the connection point of the
superconducting line explained in the Embodiment 1 is
applied to connection between the superconducting
15   magnets of a multi-layer structure. Fig. 6 shows the
conceptual drawing. The superconducting coil in the
present embodiment comprises the first layer
superconducting coil 21, the second layer
superconducting coil 22 and the third layer
20   superconducting coil 23. All coils are the solenoid
coils using the NbTi multi-filament superconducting
line. The used superconducting line has a diameter of
0.7mm, and a critical current of 800A at an external
magnetic field of 0T. Needless to say, the type of
25   superconductor of the superconducting coil, the
structure and dimensions of the superconducting line

and the structure and dimensions of the
superconducting coil need not be the same as those of
the present embodiment.

5   Table 6 shows the specifications of the coil in
the present embodiment.

Table 6

External magnetic field	1st layer	2nd layer	3rd layer
Inner diameter (mm)	600	120	180
Outer diameter (mm)	100	160	220
Shaft length (mm)	100	100	100
Rated current (A)	158		
Rated center magnetic field (T)	8.0		
Maximum empirical magnetic field (T)	8.4	5.2	3.1

10

      These coils with coil centers aligned are arranged
on the same shaft. Lead outside the first layer coil
15   28b and lead inside the second layer coil 28c are
electrically connected through the superconducting
line/superconducting line connection point 27a, and
lead outside the second layer coil 28d and lead inside
the third layer coil 28e are electrically connected
20   through superconducting line/superconducting line
connection point 27b. The lead inside the first layer
coil 28a and bus bar 25a are connected through the bus
bar/superconducting line connection point 26a, and
lead outside the third layer coil 28f and bus bar 25b
25   are connected through the bus bar/superconducting line
connection point 26b. In the present embodiment,

connection between the bus bar and coil lead is made
by soldering, but welding, mechanical contact or other
method may be used. Bus bars 25a and 25b are connected
with gas cooled type current leads 24a and 24b,

5   respectively. The gas cooled type current lead is
configured in such a way that a bundle of copper wires
are inserted into a copper pipe. Evaporation gas of
liquid helium 30 flowing out from inside the cryostat
through the clearance between copper wires, thereby

10   reducing Joule heat generation and thermal intrusion
and minimizing evaporation of liquid helium. The gas
cooled current lead can be connected with the power
supply for excitation outside the cryostat, and the
superconducting coil can be excited by the power

15   supply for excitation. The rated magnetic field of
this superconducting magnet system at the center is
8.0T when a current of 158A is supplied. The maximum
empirical magnetic field is 8.4T, 5.2T and 3.1T for
the first, second and third layer coils, respectively.

20   A superconducting line connection point having a
structure shown in Fig. 2 is used as the
superconducting line/superconducting line connection
point in this magnet system. The average particle size
of MgB_2 powder used for connection is 20 microns, and

25   indium powder having an average particle size of 5
microns is added to MgB_2 powder at the ratio of 25 % in

terms of mass ratio. The material of the coating
material of the connection point is made of copper,
and the mixture between MgB_2 powder and indium powder
is compressed to the density equivalent to 80 % or

5   more of theoretical density. The superconducting line
has stabilizer removed by chemical treatment, and the
superconducting filament is exposed to the outside.
The length of the stabilizer removed is about 30mm.
The superconducting line/superconducting line

10   connection points at two positions are located where a
leakage magnetic field of 2 to 3T is applied during
application of when rated current.

     When this magnet system was subjected to
excitation, quenching occurred at 168A. Magnetic field

15   at the center was 8.5T at this time. The present
inventors studied the status of voltage generation on
each part of the coil to find out that voltage
occurred from the first layer coil in quenching.
Occurrence of voltage was not observed at the

20   superconducting line/superconducting line connection
point.

     The present inventors changed the superconducting
line/superconducting line connection points into those
produced according to soldered connection method.

25   Excitation test was conducted to find out that
generation of voltage started on the superconducting

line/superconducting line connection points connecting the first layer coil and the second layer coil immediately after start of current application, and quenching occurred to the coil at an applied current

5   of 620A. Judging from the trend of generated voltage having been measured, it is apparent that Joule heat generation occurred as a result of increased current in the superconducting line/superconducting line connection point having changed to the non-

10   superconducting state due to leaked magnetic field, and the non-superconducting area expanded to the superconducting line area, with the result that the entire coil was quenched.

The result of the above test has make it clear

15   that high-performance, high-stability connection of the superconducting line can be ensured by using MgB$_2$ powder for the superconducting line/superconducting line connection point.

Embodiment 9

20   Fig. 7 is a cross sectional view representing the ninth embodiment of the superconducting line connection point (hereinafter referred to as "connection point") according to the present invention. Reference numerals 11a and 11b denote superconducting

25   stranded wires inside the cable-in-conduit type forcibly cooled superconductors (hereinafter referred

to as "superconductors"). The forcibly cooled
superconductor in the present embodiment is a cable-in
conduit type superconductor consisting of stranded
wires arranged inside the stainless steel-made

5   conduits 13a and 13b of cylindrical form, wherein the
aforementioned stranded wires are formed by bundling
and twisting multiple multi-filament superconducting
lines where the NbTi is used as a superconducting
material and copper as a stabilizer. NbTi was adopted

10   as a superconducting material in this embodiment, but
other superconductors can also be adopted, as
confirmed by the experiment conducted by the present
inventors. Further, aluminum, silver, copper/nickel
alloy or composite material thereof in addition to

15   copper can also be used as a stabilizer. Reference
numerals 12a and 12b denote superconducting filaments
inside the aforementioned stranded wires, and the
superconducting filament is exposed to the outside by
removing the stabilizer of the superconducting line

20   end portion by chemical treatment. The stabilizer can
be removed by mechanical cutting method in addition to
chemical treatment. Reference numerals 13a and 13b
denote superconductor conduits, which are cylindrical
pipes made of SUS304L stainless steel. In addition to

25   stainless steel, Incoloy or other alloys as well as
other metal materials can also be used as a material.

Further, the cross section can be formed in any
configuration including a rectangular shape. The
percentage of the superconducting stranded wire inside
the conduit in terms of volume is 60 % or more. The

5   exposed superconducting filament together with MgB
2powder is accommodated in the coating material 3 of
the connection point. They are crimped together with
the coating material of the connection point, and the
density of MgB_2 powder is reduced to 50 % or more of

10   the theoretical density by compression. The sleeve 14
is SUS304L-made pipe, and is arranged outside the
coating material of the connection point. It is
connected with both conduits by welding, and the
superconducting line, the coating material of the

15   connection point and MgB_2 powder are enclosed therein,
except for a refrigerant discharge port 15 as an
opening. The forcibly cooled superconductor in the
present embodiment forms part of the superconducting
coil. Fig. 7 shows superconducting coils arranged on

20   the right and left.

A refrigerant used in this embodiment is super-
critical pressure helium. If there is no problem of
pressure loss or the like, it is also possible to use
liquid, gas or supercritical pressure body of helium,

25   neon, hydrogen, nitrogen or mixture thereof, so long
as the temperature of such a substance can be kept

below the critical temperature of the applied
superconducting material. Super-critical pressure
helium flows from the end portions of the
superconducting coils on the right and left into the
5   superconductor. After cooling the entire
superconducting coil, it passes through the space
between the coating material of the connection point
and sleeve at the connection point and is discharged
from the refrigerant discharge port.

10   Fig. 8 is a schematic diagram representing the
forcibly cooled superconducting coil where
superconducting connection point according to the
present embodiment is applied. Reference numerals 51a
and 51b are superconducting coils using cable-in-
15   conduit type forcibly cooled superconductor. This coil
is produced for connection test, and uses a cable-in
conduit type superconductor where thirty-six NbTi
superconducting lines having a diameter of 0.9mm are
accommodated into a conduit with an inner diameter of
20   7mm. It is a ten-turn solenoid coil having a diameter
of 200mm. The coil constant is as small as 0.00001 or
less, but the critical current of the superconductor
is as great as 3600A in the external magnetic field of
5T. Numeral 52 denotes a connection point, and the
25   cross section of the MgB_2 powder enclosed in the
coating material of the connection point in this

position is about three times that of the
superconducting stranded wire. The density of MgB_2
powder portion is reduced to 60 % of the theoretical
density by compression. Numerals 54a and 54b denote
5   bus bars for current supply, and the 53a and 53b
denote a connection point between a superconducting
coil and bus bar. Current is applied in series to two
superconducting coils from the coil excitation power
supply 55 via the bus bar through the connection point
10   between the superconducting coil and bus bar. On the
other hand, super-critical pressure helium is
generated by a super-critical pressure helium
generating apparatus 56, and is separated into two
streams at a discharge port 57 to be supplied in
15   parallel to the superconducting coil. Then it returns
from the connection point to the super-critical
pressure helium generating apparatus of a suction port
58 of the super-critical pressure helium generating
apparatus according to a circulation system. The
20   superconducting coil in the present embodiment is a
test coil, so only a very small magnetic field is
generated. Needless to say, it is possible to
configure a superconducting coil with increased
magnetic field by increasing the number of turns. Such
25   a superconducting coil may cause the number of
connection points to be increased, but this

configuration is possible because the current
application route and refrigerant circulation route
which may function as a superconducting coil are the
same. Further, the present embodiment is configured to
5   allow circulation of super-critical pressure helium.
It is also possible to use the configuration wherein a
refrigerant stored in a tank or the like is discharged
into the atmosphere outside the superconducting coil
after having cooled the superconducting coil.
10   The present inventors conducted an excitation test
using this superconducting coil arranged inside
another outer layer superconducting magnet which can
produce 5T magnetic field. This is because an external
magnetic field was essential for evaluation of the
15   superconducting coil since a test coil was used in the
present embodiment and the maximum empirical magnetic
field was small. Needless to say, if a large-sized
coil is used, magnetic field generated by the
superconducting coil itself is applied. Use of the
20   maximum empirical magnetic field of the coil itself is
preferred for evaluation. The connection point is
located slightly away from the coil, and magnetic
field of 5T is applied thereto. Further, supercritical
pressure helium has a pressure of about 10^6Pa, a
25   temperature of about 5K and a flow rate of about 5g/s.
Under these conditions, current could be applied up to

3600A which was a base angle of the superconductor.
Then current was increased beyond 3600A, and quenching
occurred to the superconducting coil although it did
not take place at the connection point. Thus, the
5   connection point in the present embodiment has a
critical current value of 3600A or more at the
external magnetic field of 5T. This was found to
provide a high performance in excess of the critical
current value. Further, when the flow rate of super-
10   critical pressure helium was halved to about 2.5g/s,
quenching did not occur at the connection point, and
it has been revealed that there is stability in
changes of the flow rate of refrigerant at the
connection point, although the critical current of the
15   coil fell down to 2800A.

The present invention reduces power consumption
due to a low electric resistance even if the
superconducting line connection point is arranged in
the magnetic field, thereby simplifying the structure
20   of the connection point.